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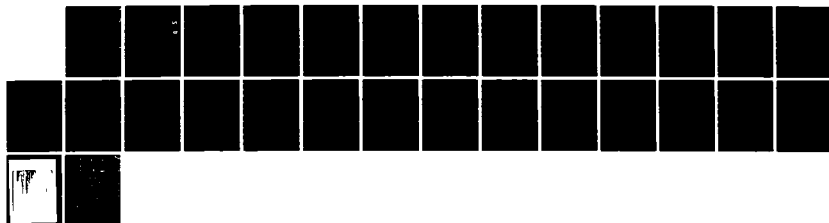
A LINEAR ARRAY FOR RAYLEIGH SCATTERING(U) CALIFORNIA
UNIV BERKELEY DEPT OF MECHANICAL ENGINEERING L TALBOT
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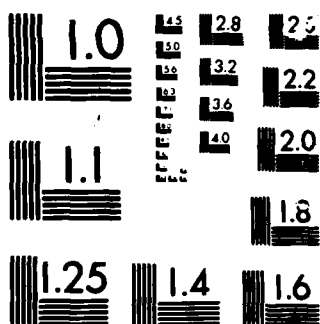
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Gas density under combustion conditions can be obtained by measuring the intensity of the molecular (Rayleigh) scattering of light from a laser beam. A system which obtains an essentially continuous record of the density along a length of the laser beam is described. The temperature and degree of combustion can thus be determined for a number of interesting combustion configurations, which will ultimately lead to a better description and understanding of combustion flow flame field phenomena. An image of Rayleigh scattered light from the combustion region is projected onto a monolithic self-scanning linear photodiode array by means of a lens, bandpass filter, slit, image intensifier, and fiber optic reducer. The video output of the linear array is digitized and stored, creating a space-time map of the density which can be visualized and manipulated as an image. Analysis of these images by image processing techniques gives qualitative and quantitative information about such features of the combustion zone as flame wrinkling and periodicity, flame thickness and continuity, and other structural and time dependent properties in the combustion region.

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ABSTRACT (cont'd)

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A LINEAR ARRAY FOR RAYLEIGH SCATTERING

Principal Investigator: L. Talbot
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University of California, Berkeley

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Gas density under combustion conditions can be obtained by measuring the intensity of the molecular (Rayleigh) scattering of light from a laser beam. A system which obtains an essentially continuous record of the density along a length of the laser beam is described. The temperature and degree of combustion can thus be determined for a number of interesting combustion configurations, which will ultimately lead to a better description and understanding of combustion flow flame field phenomena. An image of Rayleigh scattered light from the combustion region is projected onto a monolithic self-scanning linear photodiode array by means of a lens, bandpass filter, slit, image intensifier, and fiber optic reducer. The video output of the linear array is digitized and stored, creating a space-time map of the density which can be visualized and manipulated as an image. Analysis of these images by image processing techniques gives qualitative and quantitative information about such features of the combustion zone as flame wrinkling and periodicity, flame thickness and continuity, and other structural and time dependent properties in the combustion region. Following a brief introduction, the components are described, the system performance characteristics are discussed, and an example of a processed image from a simple turbulent flame is presented.

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INTRODUCTION

The understanding of turbulent combustion phenomena has been severely limited by the lack of experimental data, even though the use of optical techniques to study combustion processes has become very popular with the development of lasers and computer controlled data acquisition. The combustion environment is severe, and the introduction of physical probes can cause gross distortion of the phenomena being observed. Non-perturbing optical image techniques, which provide visualization of some property of the combustion region, can therefore be very valuable in classifying the structure of a turbulent combustion region, and in obtaining detailed quantitative information.

In this paper, a space-time image technique giving the gas density along a continuous laser beam in the combustion region is described. This system has been named Linear Array for Rayleigh Scattering (LARS).

The complicated interplay between fluid mixing and chemical kinetics in turbulent combustion has been studied using a variety of laser light scattering techniques. The velocities of the gas in the burned and unburned regions have been measured using laser Doppler velocimetry. Single and multipoint measurements of gas, particulate and species densities, and temperature, have been measured using either Rayleigh, Mie, Raman or fluorescence scattering. Quasi-instantaneous, two-dimensional images have been obtained by spreading a laser beam into a sheet of light and recording the



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scattered light either photographically or electronically. These imaging methods are generally limited to low repetition rates, which prevents the direct analysis of time-dependent phenomena.

The intensity of the Rayleigh scattered light is proportional to the number density of the scatterers and their scattering cross section. The Rayleigh technique has therefore found extensive applications in the study of temperature in combustion systems where large density changes occur at essentially constant pressure. The combustion configuration described here is a V-shaped flame, stabilized on a thin rod mounted in a flowing turbulent combustion mixture. Such a turbulent premixed flame may be visualized as a thin interface of rapidly changing temperature sandwiched between two regions of essentially constant temperature. This thin interface is wrinkled and distorted by fluctuations in the velocity of the flow in which it is embedded. The flame itself is of the order of 1 mm thick; variations in the flow velocity change its position continuously, giving rise to its description as a wrinkled laminar flame.

Simultaneous two-point measurements of the Rayleigh scattering signal has been used with considerable success in obtaining information on the structure and shape of this turbulent flame. This success has led us to the development of the multipoint imaging system described here. This system will be very useful for the study of a wide range of turbulent

combustion configurations, both premixed and turbulent mixing controlled.

LINEAR ARRAY FOR RAYLEIGH SCATTERING (LARS)

Our previous studies of turbulent combustion made it apparent that our understanding of the complex phenomena involved was limited by the methodology employed. Digital video technology had advanced to the point a Rayleigh scattered signal could be recorded in one spatial dimension resolved into 512 points at a time resolution of 10^{-4} seconds. The sensor array, digitizer, memory and controller to achieve this were available as standard equipment. Also available was image manipulation and analysis hardware that might profitably be applied to the recorded Rayleigh signal. The integration of this equipment into a working system with such capability had not been accomplished to our knowledge. Preliminary investigations determined that at a reasonable cost it would be possible to put such a system together. A development program to create the LARS system was undertaken with the support of a DOD equipment grant.

Description

The LARS system is shown diagrammatically in Figure 1 and a detailed list of components is given in Appendix A. LARS is functionally divided into four main parts:

1. "Optical" hardware through which light is imaged onto the linear array;

2. A digital imaging subsystem which controls the array and captures the array output in memory;
3. An image processing subsystem--essentially, a dedicated computation unit with its own memory--to store and process image data and display the resultant output on a video monitor;
4. A host computer which controls these and other peripheral devices.

Both the imaging and processing subsystems operate without continual host computer intervention; they are peripheral devices capable of carrying out independent functions.

Several considerations dictated the choices for hardware components. Of primary importance, both the imaging and processing subsystems were commercially available units. The existence of software developed within the University of California for driving an image processing system also had major influence on the selection of hardware.

Optical Hardware

Advanced laser research often requires results from low light levels. Analysis of low light phenomena has greatly benefited from recent advances in fast, solid-state digital image acquisition devices and from the commercial availability of microchannel plate image intensifiers. The acquisition of very low light level events at high spatial and temporal resolution has been made possible through the coupling of these two devices.

Sensor

Two types of sensors are used to obtain images for computer-based systems: charge coupled devices (CCD) and photodiode arrays. Their technologies are very similar, but the photodiode solid-state devices have the advantage of being self-scanned arrays. Their analogue signal is not clocked out of a shift register, as in a CCD. Instead the shift register controls the insertion of the analogue charge packet from each array element onto a sense line. Sampling is directly related to the number of pixels into which the image is partitioned.

We chose a Reticon RL512SF sensor for LARS. This array has 512 elements spaced 25 μm between centers (40 diodes/mm), a 2.5 mm aperture (giving each sensor an aspect ratio of 100:1) and a fiber optic window. This self-scanning linear photodiode array provides differential serial output on a single video line, giving a discrete time analogue representation of the spatial distribution of light intensity across the array. Scanning speeds up to 10^7 pixels per second were claimed, using custom electronics and amplifiers. For the 512 element array, this corresponds to 2×10^4 lines per second scanning rate, more than adequate for continuous recording of the turbulent flow motion.

Image Intensifier

Rayleigh scattering is a weak scattering process, and even with a powerful argon-ion laser the scattered light is

of low intensity. For a measurement in an optimum system, a sufficient number of photons must be collected so that the random noise, associated with the statistical fluctuations in the number of photons, is sufficiently small. This is called "shot noise". For our case, the order of 10^3 photons must be collected for each pixel in the time between samples (10^{-4} seconds), which gives a rate of 10^7 photons per second per pixel. Since the quantum efficiency of the photocathode is at least twenty percent, the number of statistically counted plate electrons is reduced to about 200 counts per sample. Previous single point measurements made using photomultiplier tube detectors operated at this sensitivity level and noise limit.

In order to use the linear diode array, the overall light sensitivity and noise level for each pixel must come close to that of a photomultiplier for a signal level of 10^7 photons per second. This requires special care in the choice of optics, image intensifier, methods of coupling, and diode array control and amplification electronics.

The principal active element in the image intensifier used is a microchannel plate (MCP). In an MCP, a photocathode converts incident photons to electrons which are accelerated into a bundle of very small tubes, each of which is a continuous dynode type electron multiplier; these multipliers output electrons which are accelerated to strike a phosphor forming the output image. The output phosphor must have sufficiently short persistence to follow the time variation of the measured light.

The image intensifier used also has one stage of vacuum

amplification in front of the MCP, where the electrons from the photocathode are accelerated and focused onto the surface of the MCP. This results in about ten times more gain than with the MCP alone, giving a total light gain greater than 10^4 , according to the manufacturers. This order of light gain is necessary so that the signal is above the noise level of the diode array.

The image intensifier has fiber optic windows on both the input and output. The output is coupled to the photodiode array through a 2:1 fiber optic reducer, which matches the 12.5 mm long array to the 25 mm diameter intensifier. There are two advantages to such a reducer and a larger intensifier. First, the spatial resolution of the intensifier is not as great as the resolution of the array, so using the reducer results in better overall spatial resolution. Second, somewhat more light can be collected from the laser beam, resulting in a bit larger original signal for each pixel of the array. This reduces the shot noise associated with the signal and improves the overall signal-to-noise ratio.

The fiber optic surfaces are coated with an optical grease and mechanically held in contact and alignment. They are relatively easily disassembled for checking alignment and operation.

Optical Lens

A standard, fast 35 mm camera lens is used to collect the scattered light and provide an image of the laser beam on the

intensifier. This is a 50 mm focal length, $f/1.2$ lens made by Nikon. The entire assembly of lens, intensifier, fiber optics, diode array and preamplifier are mounted in an aluminum housing. This housing holds the elements in a split circular cavity, so that they can be adjusted easily for focus and clamped in position. The lens is mounted so that the end normally facing the film is pointed towards the laser beam. To image a 10 mm length of the beam, for example, the image is magnified approximately 2.5 times to 25 mm length to match the dimension of the image intensifier. A slit, constructed of two razor blades, is mounted immediately in front of the intensifier to mask out light other than that from the laser beam.

Imaging Subsystem

Only one commercially manufactured imaging subsystem (Microtex 7402) was found with sufficient speed to read the Reticon photodiode array near its maximum (10 MHz/pixel) rate. This digital imaging subsystem provides a link between the solid-state camera and Digital Equipment Corporation (DEC) mini-computer. This system was advertised as compatible with LSI 11/23, VAX and PDP-11 computers, was supported under RT, RSX, and VMS operating systems, and was capable of decoding 18- or 22-bit addresses. An image is captured as 8-bit pixels of gray-scale data, at speeds up to 5 MHz. Once initiated by the host, the system controls and completes the data acquisition; host interaction is required only at the end of the acquisition. The data is immediately available to the host.

The main components in the Microtex 7402 imaging sub-system are:

- 1) The 7402 controller generates control logic for the array, and the link to the host computer using control and status registers. Values set by the host computer in these registers control the Microtex. 256 kilobytes of high speed dual-ported memory, holding one frame 512 by 512 pixel by 8-bits, is standard with the 7402; we purchased an additional megabyte of memory to increase this capacity to five frames.
- 2) The camera interface-data conversion module (DCM), which digitizes the analogue video output of the array.
- 3) Array preamplifier and controller, which is mounted in a pod with the camera.

The Microtex modules reside in a separate Q-bus backplane. Connection is made to the host via an MDB TEV bus connector, a dual wide board in each backplane. The 7402 Controller, the DCM and the megabyte expansion memory each require a single quad-wide slot. A dual wide bus terminator completes the Microtex backplane. A single cable connects the DCM to the preamplifier pod electronics; outgoing are the array control signals; incoming is preamplified array output, a video signal.

The image acquisition system uses dual ported memory to receive the digitized video signal with 8-bits of gray scale resolution for each picture element. The entire image is memory resident, but through use of memory mapping logic only a portion of the Microtex memory occupies host address

space. The host address space contains one frame which may be sent to the image processing subsystem in a single DMA transfer.

Image Processor

Several image processors were available and suitable. These processors are dedicated pipeline computation units that work with the contents of frame buffers to perform certain operations in real time (1/30th second video frame rate). With such processors, Landsat, ERTS and other remote sensing data have been interpreted for several years; the image processing subsystem for LARS could therefore be expected to function as required without modification.

Software control of the image processor was a major concern; in image processing, a large number of sequential operations are required, with parameters and files passing along each step. Individual programs written to accomplish a given processing sequence would be specialized, complicated, and difficult to use. Software systems available from manufacturers were expensive, and none controlled the acquisition subsystem or host computer as required.

Within the constraints of the LARS project it was not possible to write a general purpose image processing system. A software system called "Daisy" had been developed by the Signal and Image Processing Laboratory, University of California, Davis (UCD). This system provides a specialized high-level language which drives an International Imaging

Systems (IIS) image processor. At UC Davis, Daisy runs on a DEC PDP 11/55 under RSX11M and is used daily for a variety of applications. Daisy greatly facilitates the interactive image processing of remote sensing and other signals and is successfully being used by non-specialists. The staff at the UCD Signal and Image Processing Laboratory had considerable expertise in image processing; their assistance was a significant asset for the LARS project.

The availability of Daisy within the UC system dictated the choice of both the image processor and operating system. An International Imaging Systems Model 70/F4 display computer was purchased for LARS digital image processing. Version 4.1a of RSX11M, with modifications required by Daisy and our particular hardware, was generated by Everett Harvey at LBL for the LARS operating system.

The IIS Model 70 processes an image 512 by 512 pixels with 8-bit intensity at each pixel, which is 512 lines from the Microtex imaging system. Three high-speed parallel pipeline processing channels perform real-time image array arithmetic functions for each primary color. The LARS IIS processor is equipped with:

- Ø Dynamic ram memory for four 512 x 512 x 8-bit refresh memory channels, and eight 1-bit graphics channels;
- Ø A look up table (LUT) in each pipeline for each refresh memory channel; LUT's map each unique input value to some predefined output value, and are used for non-linear transforms of gray levels, to produce pseudo-color, and to perform some arithmetic operations;

- ◊ An input function memory, with 12-bit input and 8-bit output, for scaling, negation, and equalization of input data;
- ◊ A feedback arithmetic/logic unit with a 16-bit "accumulator" channel for high speed recursive procedures such as convolution;
- ◊ A videometer which computes a histogram on any raw or processed image in 67 milliseconds;
- ◊ Three separate output function memories with 10-bit input and output;
- ◊ A trackball and four function switches for quick, high-level user input and interaction;
- ◊ Independent, non-destructive hardware zoom and scroll on each refresh channel;
- ◊ RS170 composite video output to drive a color monitor.

Two pieces of software were supplied with the ISS, an RSX-11M device driver (the communication link between the host and IIS) and a set of diagnostic programs which test all IIS system hardware.

We chose a 19" color monitor with RGB input capability available from a local television store for the image processor display output. Larger high-resolution monitors are normally used with image processors, but these are very expensive. Slight modification of the video output signal generated by the IIS was required to interface this monitor. Simple screen photographs taken with a single lens reflex

camera is our current method to produce LARS hard-copy output. This is the most cost-effective hard-copy method available.

IIS processors were in use with Unibus computers; interfacing an IIS and a 22-bit Q-bus host had not been done previously and was required for LARS. During planning this task did not appear to pose much difficulty. However, to obtain both hardware and software compatibility between the IIS processor, the Daisy software, the 22-bit Q-bus, 11-23 computer with 1.25 Mbyte of memory, a 500 Mbyte disk drive, a streaming tape drive, and the Microtex imaging subsystem posed considerable difficulty. Several modifications to the software were necessary.

DISCUSSION

Remote sensing began early in this century when photographs of the earth's surface were taken from aircraft. It was not until the late 1960s, when the first multispectral scanners were flown on aircraft, that any interest arose in quantitative processing and analysis of numerical data from remote sensing. Since the launch and success of the Landsat satellites, digital image processing has become an increasingly familiar and useful tool.

The principles for manipulating digital images derive from these studies of remote sensing data, mostly from multispectral scanner systems (MSS) such as those on the Landsat satellites. But an image can also be a photograph digitized

by an optical scanner, or any other phenomenon capable of being similarly digitized. An "image", therefore, is a two-dimensional array of numbers, each representing the brightness (intensity) of a small elemental area of the overall image. These discrete picture elements are called "pixels".

Signal processing has been used to manipulate images from diverse sources, often with striking success. Various numerical techniques may be applied to the intensity values of the original image, creating a new (enhanced) image. The principal idea behind image processing is to render the image more informative, and to extract signal from noise.

It is important to note the three characteristics of a pixel:

- 1) Its numerical value: one of many intensities that make up the digital image;
- 2) The linear dimension between adjacent pixels, projected onto whatever is being imaged the spatial resolution;
- 3) The time between consecutive samples or the temporal resolution.

Pixel intensity suffers from the limitation inherent to all digital data, which is the problem of representing continuous scene radiance using a finite number of bits. The present image processing subsystem operates with an 8-bit pixel of intensity, giving 256 gray levels or unique colors.

PERFORMANCE

Spatial Resolution

The present optical arrangement projects approximately 10 mm of the laser beam onto the 512 elements of the photodiode array, giving an effective separation of 20 μm . The main loss of spatial resolution occurs in the image intensifier, which has an advertised resolution of 10 line pairs per mm. This would result in a resolution of about 40 μm at the laser beam, or of about 2 pixels. A proper determination of the spatial resolution has not yet been made, but the quality of the images indicates that the true resolution is of this order.

Temporal Resolution

The Mixrotex 7402 can read the linear array at a maximum pixel rate of 5 MHz, which gives a line rate about 10 kHz. A reset before each line adds a slight delay: the fastest achievable line rate is 103.6 microseconds if all 512 elements are read. Adjoining pixels along a line are 200 nanoseconds apart; adjoining pixels between lines are 103.6 microseconds apart.

A LARS image is spatial along the horizontal axis and temporal on the vertical axis. At present, a single LARS "shot" acquires 512 pixels per line for a maximum of 2560 lines, taking 0.265 seconds. One of these images contains more than 1.3 Mbytes. With LARS we can acquire data at light levels as low as a few hundred photons per square millimeter

per scan line, in a ten-thousandth of a second. This is the same order of sensitivity that is achieved using photo-multipliers.

Figure 2 shows an example of the kind of data that can be obtained with LARS. The flow system is a rod-stabilized V-shaped ethylene-air flame with an equivalence ratio of 0.65, propagating into an oncoming stream with mean velocity of 5 m/s and free stream turbulence intensity of about 2 percent. These conditions are typical for the production of a wrinkled laminar flame front, although the turbulence level is quite low. A 1 cm section of a laser beam directed through the flame front transverse to the free stream direction about 25 mm downstream of the flameholder was imaged on the linear array and scanned at a 10 kHz rate. Since the time to sweep one line is 103.6 μ sec, and since the image contains 512 lines, the elapsed time from the top of the image to the bottom is $\sim .053$ sec. During this period, the image reveals perhaps eleven flame excursions of the order of a few mm in distance, corresponding to a dominant wrinkling frequency of the order of 200 Hz. The burned gas is on the left, corresponding to the dark (red false color) region, and the unburned gas is on the right, corresponding to the light (blue false color) region. The wrinkling scale and frequency are consistent with measurements obtained by two-point Rayleigh scattering, although of course much more information is contained in this LARS image than is contained in a two-point Rayleigh time series.

We plan first to use LARS to study in greater detail than has heretofore been possible the structure of wrinkled laminar flames. Subsequent applications could include recirculation and flame stabilization zones, and reacting shear layers and turbulent boundary layers.

APPENDIX A - Equipment List

Host Computer

Backplane, Q-bus, Netcom HV-1148

power supply

front panel switches

9 quad-wide slots

22-bit addressing

CPU, LSI 11/73, DEC KDJ11-AA

16-bit DCJ11 CMOS processor

8kbyte cache

32-bit internal data path

22-bit addressing

separate instruction and data space

Memory, Clearpoint QRAM-22

22-bit addressing

block mode DMA

Serial Interface, GTSC 304B

DEC DLV11-J equivalent

4 serial input lines with selected baud rates

Disk controller, Emulex SC03/BX

SMD interface

1.8 Mbyte/second data rate

clock control

22-bit addressing

self diagnostics

DEC transparent

8kbyte data buffer

Disk drive, Fujitsu M2351/A "Eagle"

- 10.5 inch Winchester fixed disk
- 6 platters in completely sealed disk enclosure
- 18 millisecond average positioning time
- 1.859 megabyte/second data transfer rate
- standard SMD interface
- 842 cylinders, 880 tracks/inch, 28160 bytes/track
- 474 megabytes capacity

Cables, disk Emulex SV111 2325, 25 feet

Tape controller, Emulex TC-02

- 1/2" streaming tape drive
- 1600 bpi ANSI PE compatible
- 22-bit addressing
- 250 kbyte/second data rate
- Q-bus 16-bit word NPR data transfers
- parity check of all transfers
- 5 level interrupt
- DEC transparent

Tape drive, Cipher F880-II

Floppy disk drive, 8" Tandon TM848-2

Floppy disk controller, Quadology DSD 4140-03

Enclosure, dual 8" thin-line, DTL 002

Terminator and boot card, Netcom MPV-11 CB

Software licenses, DEC QJB46-DZ and QY668-DZ

Optical Hardware

Lens, SLR, 50 mm focal length, f1.2, Nikon

Multilayer dielectric bandpass filters, centered at 488
or 514 nanometer

Image intensifier, Microchannel plate, 25 mm diameter Varo

Fiber optic image reducer, 2:1, 25 mm to 12.5 mm

Lens tube, designed and built at UCB

lens mount

slit mount

filter mount

intensifier mount

light-tight

3 transverse stages, micrometer, for x-y-z positioning of
lens tube

Imaging Subsystem

Sensor, linear array, Reticon 512SF

fiber optic window

512 element

25 micrometer spacing between diodes

2500 micrometer aperture

5 MHz sampling rate

Microtex 7402 subsystem

Backplane, Q-bus

power supply

front panel switches

9 quad-wide slots

22-bit addressing

7402-8003-3a

7430-8010-2a

Aluminum pod
pod cable
pod electronics, array driver
DCM-SA, single camera, 8-bit, 10 MHz
Cables, expansion, MDB 22B

Image Processing Subsystem

Bus connector, 18-bit
Processor, International Imaging Systems model 70/F4
pipeline display processor
four refresh memory channels, 512 x 512 x 8-bit
eight graphics overlay channels
trackball and cursor
videometer
feedback arithmetic/logic unit
input function memory, 12-bit input and 8-bit output
RSX-11M device driver
diagnostic interpreter and test programs
Color monitor, Sony KX-1211
Software for IIS processor, "Daisy"
from the Signal and Image Processing Laboratory,
University of California, Davis.

Miscellaneous

Rack, main LARS
power line, 70 feet
power distribution, three 20 amp breakers
terminal table
Rack, intensifier power supply and voltage divider.

Linear Array for

Rayleigh Scattering

LARS

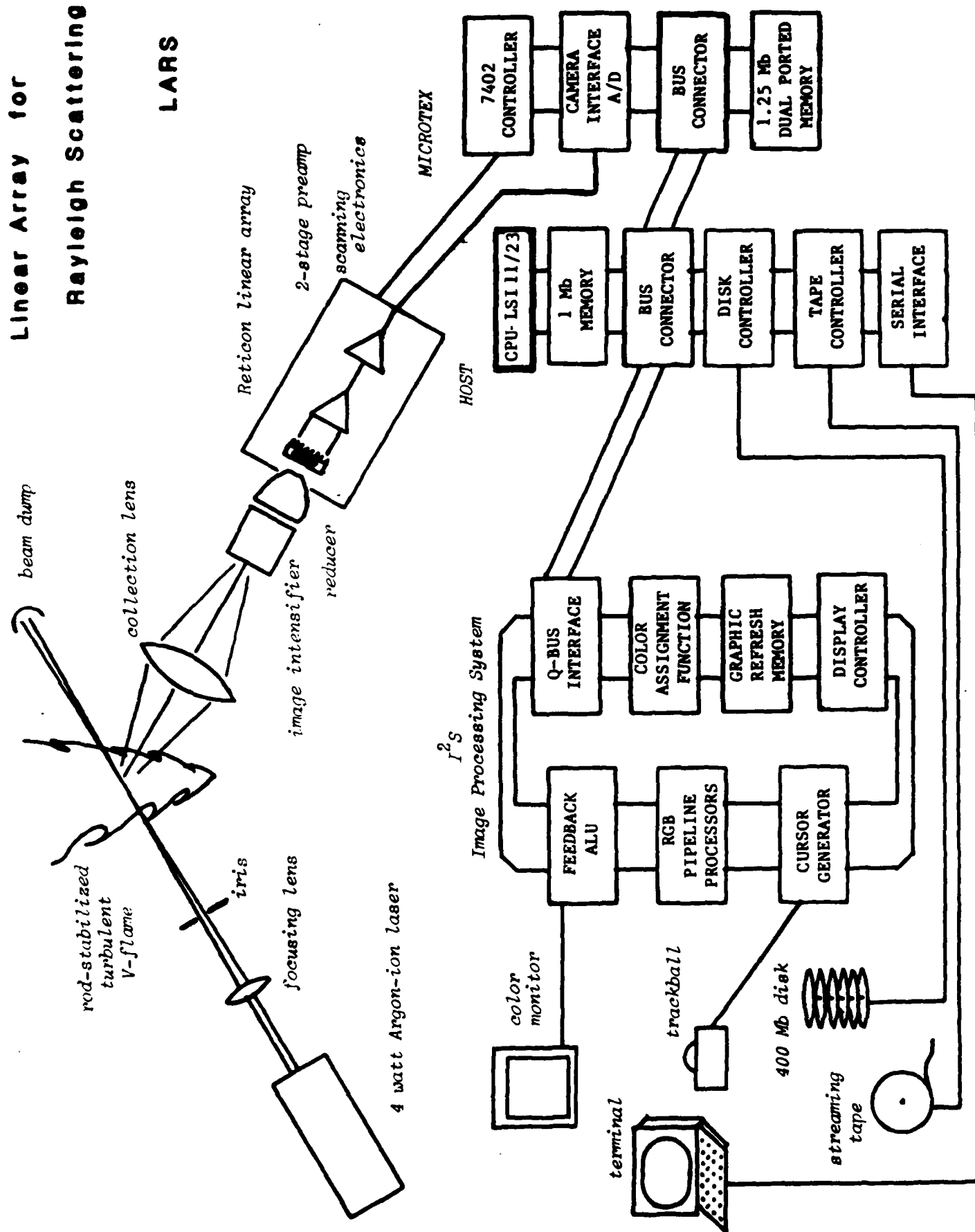


FIGURE 1



FIGURE 2 LARS Image of a Wrinkled Laminar Flame Sheet

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